

Fluctuations and asymmetric jet events in Pb Pb collisions at the LHC

Matteo Cacciari,^{1,2} Gavin P. Salam^{3,4,1} and Gregory Soyez⁵

¹LPTHE, UPMC Univ. Paris 6 and CNRS UMR 7589, Paris, France

²Université Paris Diderot, Paris, France

³CERN, Department of Physics, Theory Unit, CH-1211 Geneva 23, Switzerland

⁴Department of Physics, Princeton University, Princeton, NJ 08544, USA

⁵Institut de Physique Théorique, CEA Saclay, CNRS URA 2306, F-91191 Gif-sur-Yvette, France

Abstract

Recent LHC results concerning full jet-quenching in PbPb collisions have been presented in terms of a jet asymmetry parameter, measuring the imbalance between the transverse momenta of leading and subleading jets. We examine the potential sensitivity of this distribution to fluctuations from the heavy-ion background. Our results suggest that a detailed estimate of the true fluctuations would be of benefit in extracting quantitative information about jet quenching. We also find that the apparent impact of fluctuations on the jet asymmetry distribution can depend significantly on the choice of low- p_t threshold used for the simulation of the hard pp events.

In the quest to understand the properties of the medium generated in high-energy heavy-ion collisions, the past decade has seen extensive study of medium-induced modifications to the production of high transverse momentum objects [1]. It has been conclusively established at RHIC that the spectra of high-momentum hadrons are significantly suppressed, by a factor of $R_{AA} \simeq 0.2$ relative to the appropriate rescaling of the pp spectra. This effect is generally attributed to their (or their originating parton's) interaction with the medium.

Recently, significant attention has been directed to jets. Compared to hadrons, jets are interesting because, at least in pp collisions, there is a closer, and perturbatively quantifiable, connection between a jet's momentum and that of its originating parton. STAR [2] and PHENIX [3] have presented first (preliminary) measurements of full jets produced in AuAu collisions with transverse momenta in the 20 – 40 GeV range and found that jet spectra are also suppressed, though by a potentially more modest factor than for hadrons. In the past weeks, ATLAS [4] has published studies of the *correlations* between the momenta of the two leading jets, with the striking observation that a significant fraction of

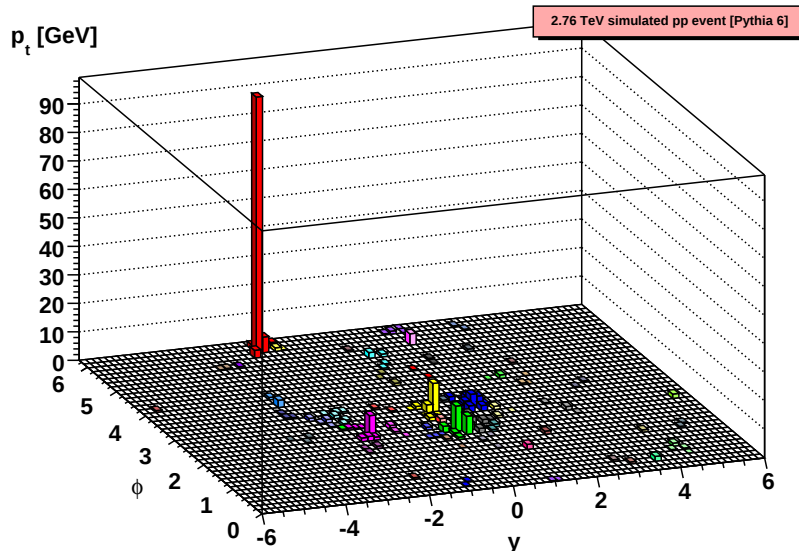


Figure 1: A simulated pp event from Pythia 6.423 (centre-of-mass energy $\sqrt{s} = 2.76$ TeV; the missing transverse energy was zero). We find that for 1 in every 300 events with a jet with $p_{t1} > 100$ GeV, the second hardest jet has $p_{t2} < p_{t1}/3$. A more accurate estimation of this number would benefit from the combination of 2-jet, 3-jet, 4-jet, $\dots$ samples, using for example one of the multijet matching methods reviewed in [7].

events show a strong imbalance between the p_t 's of the leading jet and the first subleading jet on the opposite side of the event. CMS has shown similar preliminary results in Ref. [5] and first phenomenological interpretations have been given in Ref. [6].

Such imbalances can occur also in normal pp events, due to emission of multiple gluons (cf. the simulated Pythia event shown in fig. 1), but they are quite rare. To quantify how much more often they arise in Pb Pb collisions, ATLAS and CMS have shown distributions of the jet asymmetry A_J

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad (1)$$

expressed in terms of the transverse energies of the leading and subleading jets, respectively E_{T1} and E_{T2} . The main quantitative evidence for jet quenching comes in the form of a significant enhancement of the asymmetry in the region around $A_J \simeq 0.4$ (fig. 3 of [4] and p. 26 of [5]).

In extracting the distribution of A_J , the experiments must contend with the fact that each jet may be contaminated with $\mathcal{O}(100 - 150 \text{ GeV})$ of transverse momentum from the medium particles, usually referred to as the background.¹ To calculate the A_J for a given dijet event, each jet's momentum is corrected for the expected level of background activity

¹The distinction between medium particles and jet particles is not necessarily very legitimate physically, however it may still make sense to think of an expected level of background transverse momentum.

in the jet, usually estimated from the activity elsewhere in the event, preferably at similar rapidities (see e.g. [8, 9, 4]). Such a correction cannot, however, account for the fact that the background fluctuates from point to point within the event (even at the same rapidity), so that the momentum subtracted from the jet will inevitably differ from the background actually present in the jet; nor does it account for fluctuations in the detector’s response to the background and jet particles.

Fluctuations are of course a common issue for jet measurements even in pp collisions, notably due to randomness in the response of calorimeters. However two novelties may be relevant concerning fluctuations for heavy-ion collisions. Firstly the LHC heavy-ion medium has only just been produced and it is probably fair to assume that its fluctuations² are less well understood than those of the detectors, which have been the object of study for many years. Secondly, the absolute size of detector fluctuations scales roughly as the square-root of the jet energy, meaning that they are less important for low- p_t jets than for high- p_t jets, whereas background fluctuations are probably largely independent of the jet’s p_t .

This last point is relevant because of the way in which fluctuations can affect the A_J distribution. The experimental analyses of the A_J distribution select events in which the leading jet passes some high- p_t cut, say $p_t > 100$ GeV. Events with a genuine high- p_t jet are rare. There are many more low- p_t dijet events and in some small fraction of cases the background under one of the jets may fluctuate upwards causing the jet to pass the high- p_t cut. Such events will naturally have a large jet asymmetry, since there is no reason for the balancing jet to also have a positive background fluctuation. The relative contributions of different classes of events depends on the interplay between the rareness of large background fluctuations and the rareness of high- p_t jet production as compared to low- p_t jet production. While one can in principle estimate the potential severity of this problem from Monte Carlo simulations, it is debatable whether reliable enough descriptions of the PbPb medium produced at high energy exist. Guidance from experimental measurements is therefore paramount.

One parameter that is indicative of the size of the fluctuations in the reconstructed jet p_t is their standard deviation, which we call σ_{jet} . ATLAS [10] has presented preliminary results for the fluctuations from one calorimeter tower to the next. If scaled up by the square-root of the number of towers in a jet (about 50 for an $R = 0.4$ jet with towers of size 0.1×0.1 in rapidity and azimuth), it would suggest a value $\sigma_{\text{jet}} \simeq 8.5$ GeV for the most central set of events. On the other hand, the scaling of the tower fluctuations by the square-root of the number of towers may not be a safe way of extrapolating tower fluctuations to σ_{jet} , insofar as the background could well have local correlations (there is no clear reason for the correlation length of such fluctuations to necessarily be smaller than the calorimeter tower size). Furthermore there can be other factors that contribute to a degradation of resolution, such as back reaction [11] and fluctuations in the event-by-event (or calorimeter-strip) estimation of the background level (as discussed in sections 3.5 and

²Including their standard deviation, correlations from point to point within the event, non-Gaussianities, etc.

A.1 of [9]).

Another way in which one may attempt to deduce the level of the fluctuations is from a preliminary inclusive jet spectrum for 0 – 100% centrality (p. 41 of [10]), which displays a region of near Gaussian p_t -dependence for $p_t \lesssim 50$ that is strongly suggestive of an origin due to fluctuations, and compatible with $\sigma_{\text{jet}} \simeq 14$ GeV. One would then expect the corresponding σ_{jet} for 0 – 10% central events to be somewhat larger.

The tension between the two estimates of σ_{jet} given above is obviously a concern, leading to speculation of what the true size of fluctuations is. To provide simple insight into whether similar values of σ_{jet} may lead to sizable (but unrelated to quenching) effects on the dijet asymmetry, we have carried out the following “toy” analysis. We generate jet events with Pythia [12] (version 6.423, DW underlying-event tune [13]). To mimic the effect of residual fluctuations following background subtraction, we then add to the p_t of each jet a random fluctuation, generated according to a Gaussian distribution with mean 0 and standard deviation σ_{jet} , independently of the jet p_t . These choices correspond to a perfect estimate of the average background that needs subtracting in each event and the assumption that detector fluctuations are negligible relative to background fluctuations. We select events in which the leading jet has $p_t > 100$ GeV, the subleading jet has $p_t > 25$ GeV, both have rapidities $|y| < 2.8$ and are separated in azimuth by $|\Delta\phi| > \pi/2$ and for these events plot the corresponding distribution of A_J , similarly to the ATLAS analysis [4].

The filled black points in fig. 2 show our results for four different values of σ_{jet} . One sees a clear distortion of the A_J distribution as σ_{jet} is increased, reminiscent of the pattern seen by ATLAS and CMS with increasing centrality. One key element of our simulation is that in generating the filled black points we chose a fairly low minimum p_t cut, $p_t^{\text{min}} = 30$ GeV, for the underlying Pythia $2 \rightarrow 2$ scattering, and also verified that further lowering this cut made no difference for our values of σ_{jet} . With a larger choice, $p_t^{\text{min}} = 70$ GeV (shaded region),³ which would be perfectly adequate for low σ_{jet} , one notices that a significant part of the effect of the background fluctuations can be missed for larger σ_{jet} . This leads to the obvious implication that the choice of p_t^{min} can play an important role, especially if σ_{jet} happens to be large (or, as we have also found, if there are significant non-Gaussianities in the fluctuations⁴).

A complementary investigation into the impact of fluctuations can be obtained by embedding Pythia events into a simulated PbPb background. A similar investigation was carried out by ATLAS, embedding events into PbPb events as simulated by an ATLAS-specific version of HIJING [17]. Our analysis will differ in that we study HYDJET [18] rather than HIJING and use also a lower p_t cutoff for the Pythia events. The tune we use for HYDJET⁵ gives an average background level of 210 GeV per unit area for 0 – 10%

³We understand that this was the value used in refs. [4, 10]

⁴Significant non-Gaussianities have been observed in [14].

⁵The tuning parameters used to simulate LHC events at $\sqrt{s} = 2.76$ TeV with HYDJET v1.6 have been extrapolated between the 200 GeV (RHIC) and 5.5 TeV (LHC at designed energy) values used in [9] (footnote 7), namely `nh` = 25600, `ylf1` = 3.9, `ytf1` = 1.46 and `ptmin` = 7.54 GeV. Quenching effects have been switched off by setting `nhse1` = 1. The embedded events come from Pythia version 6.423, tune DW, run at $\sqrt{s} = 2.76$ TeV.

Pythia with Gaussian smearing

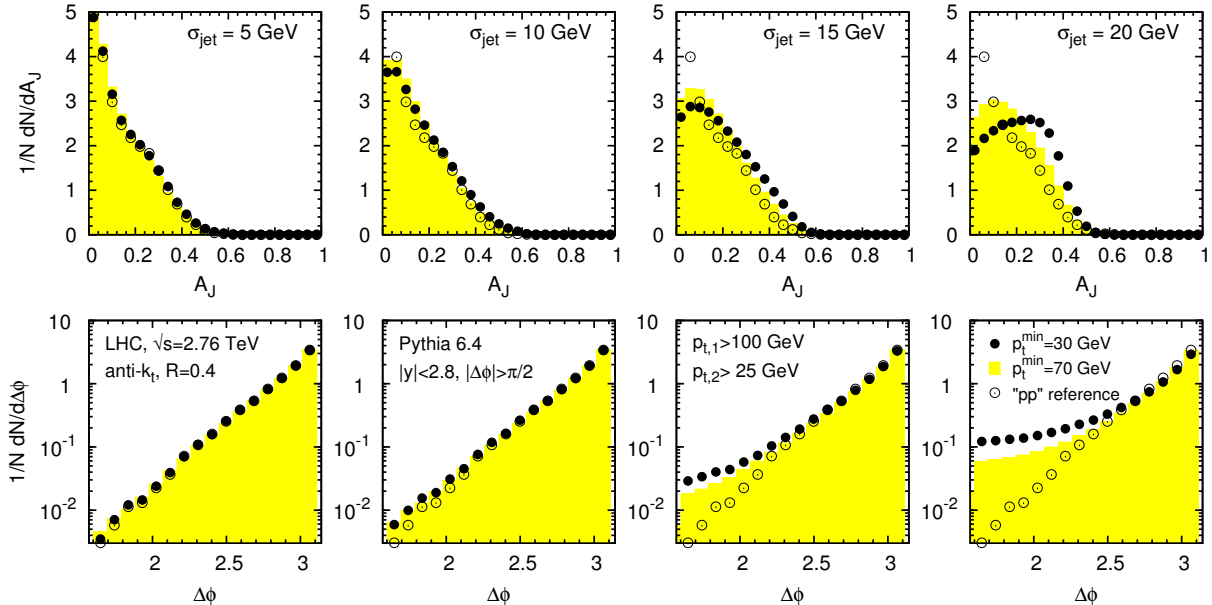


Figure 2: Simulated distribution of A_J and $\Delta\phi$, as obtained when smearing the p_t of jets from Pythia 6.4 (DW tune [13]) by an amount σ_{jet} . None of the results in this figure involved jet quenching. Four different σ_{jet} values are shown, and for each plot there are results from Pythia simulations with two different generation cutoffs on the $2 \rightarrow 2$ scattering, $p_t^{\text{min}} = 30 \text{ GeV}$ and $p_t^{\text{min}} = 70 \text{ GeV}$, so as to illustrate its impact. The results labelled “pp” reference always correspond to $p_t^{\text{min}} = 30 \text{ GeV}$ with no smearing. Jet clustering has been performed with the anti- k_t algorithm [15] with $R = 0.4$, as implemented in FastJet [16].

centrality and $|\eta| < 2.8$, compatible with the average jet contamination found by ATLAS, and an average charged-particle multiplicity for $0 - 10\%$ centrality of 1400 for $|\eta| < 0.5$], which is reasonably consistent with that measured by ALICE [19]. HYDJET’s simulation of quenching has been turned off, to avoid the potential confusion that might arise from the quenching of hard jets associated with the PbPb simulation rather than with the embedded Pythia event. Since detectors can have an impact on fluctuations, we have also processed the events through a (over-)simplified calorimeter simulation.⁶ To subtract the background from jets we have taken the area/median method of [11, 20], using, for the estimation of the background density, a (rapidity) StripRange of half-width 0.8 centred on the jet to be subtracted, as described in more detail in [9]. This method should perform similarly to the ATLAS method of background subtraction. With this setup, for collisions in the 0-10% centrality range, we find fluctuations per unit area of about 23 GeV corresponding,

⁶Charged particles with $p_t < 0.5 \text{ GeV}$ are first removed, and the remaining particles are put on a calorimeter of size 0.1×0.1 extending up to $|\eta| = 4.5$ with uncorrelated Gaussian fluctuations of width $0.8/\sqrt{E}$ in each cell and a 0 GeV cell threshold. The number quoted above for the average energy flow are those obtained at calorimeter level.

Pythia embedded in HYDJET

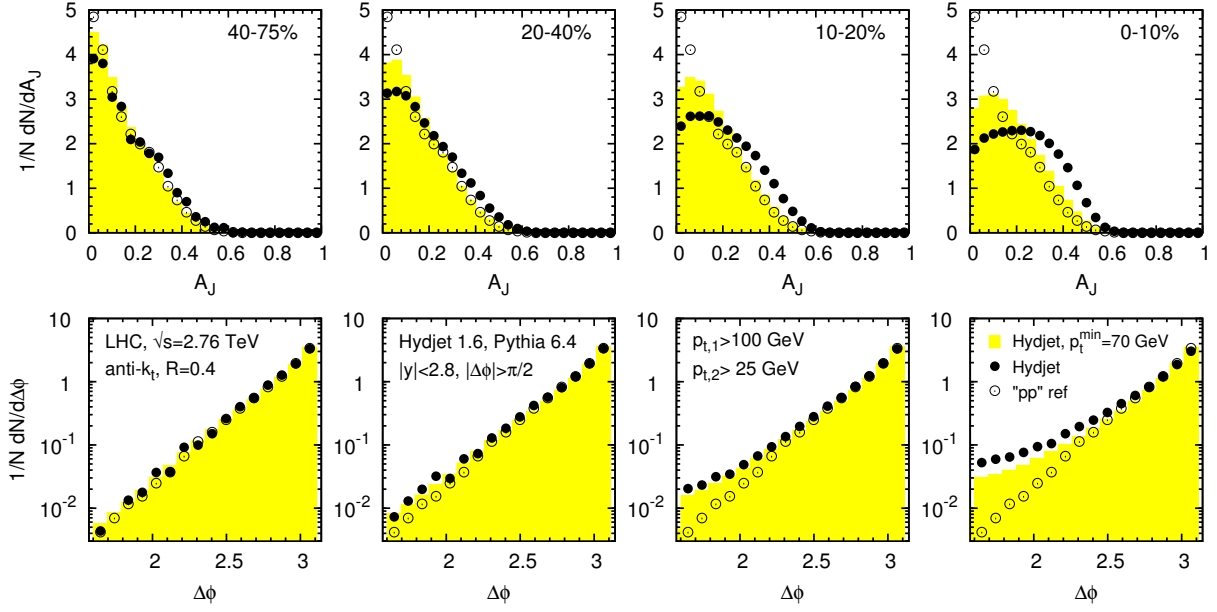


Figure 3: Simulated distribution of A_J and $\Delta\phi$, as obtained when embedding Pythia events in a PbPb background described by HYDJET 1.6. None of the results in this figure involved jet quenching and the results obtained with HYDJET include a simple calorimeter simulation. Four different centrality regions are shown as indicated in the plots on the top row. For each plot there are results from Pythia simulations with two different generation cutoffs on the $2 \rightarrow 2$ scattering, $p_t^{\min} = 10$ GeV and $p_t^{\min} = 70$ GeV, so as to illustrate its impact. The results labelled “pp” reference always correspond to those of Fig. 2. Jet clustering has been performed with the anti- k_t algorithm [15] with $R = 0.4$, as implemented in FastJet [16] and the heavy-ion background subtraction has been performed as described in [9] with the background density estimated using a StripRange of half-width 0.8 centred on the jet being subtracted.

for anti- k_t jets of radius $R = 0.4$, to an expected σ_{jet} of 16 GeV and a measured σ_{jet} of 17 GeV.

The results we obtain from the HYDJET+Pythia simulations are presented in Fig. 3 for four centrality ranges. The empty circles labelled “pp” reference correspond to plain Pythia results as for Fig. 2. The filled black points and shaded histogram correspond to our embedding in HYDJET events and differ only by the $p_t^{\min}$ of the underlying Pythia $2 \rightarrow 2$ scattering: 10 GeV has been used for the former and 70 GeV for the latter.⁷

The evolution of the A_J distribution with increasing centrality in HYDJET displays a pattern similar to that observed for the Gaussian smearing with increasing σ_{jet} . If

⁷HYDJET itself generates many additional pp $2 \rightarrow 2$ scatterings for each heavy-ion collision, each with $p_{t,\text{min}} = 7.54$ GeV. When embedding a jet event with a 10 GeV cutoff, in most cases the two hardest jets actually originate from these additional HYDJET pp scatterings.

anything, the distortion of the A_J distribution for 0 – 10% central HYDJET collisions is slightly more pronounced at large A_J than with the highest Gaussian smearing we used, despite the smaller σ_{jet} value from HYDJET. This could perhaps be a consequence of non-Gaussianities in its fluctuations. The HYDJET results also confirm the importance of the choice of p_t^{min} cut on the $2 \rightarrow 2$ scatters.

While the above results suggest that fluctuations could be of relevance in interpreting the A_J distributions, one should not forget that the experiments have studied observables intended to signal the possible presence of important effects from fluctuations. One such observable is the fraction of energy inside a core of $R = 0.2$ within the jet. A fluctuation that enhances the leading jet's p_t would not necessarily be close to the centre of the jet and so should on average reduce the core energy fraction.⁸ Preliminary data from ATLAS (p. 34 of [10]) show a stronger reduction in core energy fraction with increasing centrality than in the ATLAS HIJING simulations. In our HYDJET simulations, the core energy fraction decreases yet more rapidly, which at first sight suggests that its fluctuations could be excessive. On the other hand, we find that the agreement in absolute value is better for central collisions than for peripheral collisions, complicating the interpretation.⁹ Another cross-check on fluctuations comes from the A_J distribution for jets with $R = 0.6$ (e.g. p. 48 of [10]). Since fluctuations should increase for a larger R , one would expect them to lead to an enhancement of the high A_J part of the $R = 0.6$ distribution. Vacuum QCD (and jet quenching) are expected to act in the opposite direction. The (unquenched) HYDJET simulation shows a fairly complicated behaviour however: the large A_J ($\gtrsim 0.4$) part of the distribution barely changes in going from $R = 0.4$ to $R = 0.6$, while the distribution increases for $A_J = 0.2$ (and decreases for A_J near zero). In contrast, the preliminary data decrease at large A_J and, within the (large) errors, barely change for moderate and small A_J , suggesting, possibly, some non-trivial interplay between an effect such as quenching and fluctuations.

To conclude, it is not our intention to claim that the striking results of [4] are largely an artefact of fluctuations. Nevertheless fluctuations can significantly affect the main observable there, the centrality dependence of the A_J distribution. A precise estimate of the contribution of fluctuations is therefore important to be able to quantify the nature of the quenching that is present in the data. As discussed above, we have not found it to be simple to come to a firm, quantitative conclusion concerning the relative contributions of fluctuations and effects such as jet quenching. On one hand, attempts to directly deduce the level of jet fluctuations from tower fluctuations and from the low- p_t part of inclusive-jet spectrum lead to different conclusions. On the other hand, observables such as the jet core energy fraction and the R -dependence of the A_J distribution, which should help constrain fluctuations, mix many different physical and detector effects; it is probably only through an exhaustive investigation of different scenarios for fluctuations and quenching, including detailed detector simulation, that the information they contain could be fully exploited. It

⁸This though is not entirely trivial, because the fluctuation may itself displace the centre of the jet. Furthermore any quenching of the leading jet may also reduce the core energy fraction.

⁹For the subleading jet, the centrality dependence is very similar for data and HYDJET, but the data are systematically about 0.15 below HYDJET.

might therefore be beneficial to obtain a more direct estimate of the nature and impact of the fluctuations. This could be achieved, for example, by embedding simulated (or even real) pp events in real heavy-ion events (as discussed e.g. in [14, 5]), as long as the former are generated with a sufficiently broad range of p_t , and/or through a dedicated study of the spectrum of fluctuations of the background. Depending on how relevant fluctuations turn out to be, then it may be advantageous to attempt to unfold their effect. Their impact can also be reduced significantly by raising the jet p_t thresholds. Additionally it may be of interest to investigate methods to suppress fluctuations (the method of [8], or filtering/trimming/pruning [21, 22, 23]), even if one should be aware that such methods can introduce biases of their own in the presence of jet quenching [2, 9].¹⁰

Acknowledgements

We wish to thank Tancredi Carli, Brian Cole, Peter Jacobs, Michelangelo Mangano, Mateusz Ploskon, Sevil Salur, Peter Steinberg and Urs Wiedemann, for helpful conversations, comments and additional information. This work was supported in part by grants ANR-09-BLAN-0060 and PITN-GA-2010-264564.

References

- [1] U. A. Wiedemann, [arXiv:0908.2306 [hep-ph]]; D. d’Enterria, [arXiv:0902.2011 [nucl-ex]]; J. Casalderrey-Solana, C. A. Salgado, Acta Phys. Polon. **B38** (2007) 3731-3794. [arXiv:0712.3443 [hep-ph]]; A. Majumder, M. Van Leeuwen, [arXiv:1002.2206 [hep-ph]]; P. Jacobs, X. -N. Wang, Prog. Part. Nucl. Phys. **54** (2005) 443-534. [hep-ph/0405125]; M. Gyulassy, I. Vitev, X. -N. Wang *et al.*, In “Hwa, R.C. (ed.) et al.: Quark gluon plasma” 123-191. [nucl-th/0302077].
- [2] S. Salur [STAR Collaboration], Eur. Phys. J. C **61** (2009) 761 [arXiv:0809.1609 [nucl-ex]]. S. Salur [STAR Collaboration], Nucl. Phys. A **830** (2009) 139C [arXiv:0907.4536 [nucl-ex]]; M. Ploskon [STAR Collaboration], Nucl. Phys. A **830** (2009) 255C [arXiv:0908.1799 [nucl-ex]]. E. Bruna [STAR Collaboration], arXiv:1010.3184 [nucl-ex].
- [3] Y. S. Lai for the PHENIX collaboration, arXiv:0911.3399 [nucl-ex].
- [4] The ATLAS Collaboration, arXiv:1011.6182 [hep-ex].

¹⁰ Such methods discard low-momentum components of the jets, exploiting the fact that the background is almost entirely made of low-momentum particles, while for a pp jet only a small fraction of its total momentum is contained in low-momentum components. In the presence of quenching, however, a much larger, but unknown, fraction of the jet’s energy may be concentrated in low-momentum components. Discarding these components is then not without risks. Special care should also be taken with infrared or collinear unsafe seeded jet algorithms, as quenching may cause a jet’s high central energy density (the seed) to be redistributed over a broader region of the calorimeter.

- [5] B. Wyslouch for the CMS collaboration, presentation at CERN, 2 December 2010, <http://indico.cern.ch/getFile.py/access?contribId=1&resId=1&materialId=slides&confId=114939>
- [6] J. Casalderrey-Solana, J. G. Milhano, U. A. Wiedemann, [arXiv:1012.0745 \[hep-ph\]](#).
- [7] J. Alwall *et al.*, Eur. Phys. J. C **53** (2008) 473 [[arXiv:0706.2569 \[hep-ph\]](#)].
- [8] O. Kodolova, I. Vardanian, A. Nikitenko *et al.*, Eur. Phys. J. **C50** (2007) 117-123.
- [9] M. Cacciari, J. Rojo, G. P. Salam and G. Soyez, [arXiv:1010.1759 \[hep-ph\]](#), to appear in Eur. Phys. J. C.
- [10] B. Cole for the ATLAS collaboration, presentation at CERN, 2 December 2010, <http://indico.cern.ch/getFile.py/access?contribId=0&resId=5&materialId=slides&confId=114939>
- [11] M. Cacciari, G. P. Salam and G. Soyez, JHEP **0804** (2008) 005 [[arXiv:0802.1188](#)].
- [12] T. Sjostrand, S. Mrenna and P. Skands, JHEP05 (2006) 026 [[hep-ph/0603175](#)].
- [13] M. G. Albrow *et al.* [TeV4LHC QCD Working Group], [arXiv:hep-ph/0610012](#).
- [14] P. Jacobs, [arXiv:1012.2406 \[nucl-ex\]](#).
- [15] M. Cacciari, G. P. Salam and G. Soyez, JHEP **0804** (2008) 063 [arXiv:0802.1189 \[hep-ph\]](#).
- [16] M. Cacciari and G. P. Salam, Phys. Lett. B **641** (2006) 57 [[hep-ph/0512210](#)]; M. Cacciari, G. P. Salam and G. Soyez, <http://www.fastjet.fr>.
- [17] X. -N. Wang, M. Gyulassy, Phys. Rev. **D44** (1991) 3501-3516.
- [18] I. P. Lokhtin and A. M. Snigirev, [hep-ph/0312204](#).
- [19] K. Aamodt *et al.* [The ALICE Collaboration], [arXiv:1012.1657 \[nucl-ex\]](#); K. Aamodt *et al.* [The ALICE Collaboration], [arXiv:1011.3916 \[nucl-ex\]](#).
- [20] M. Cacciari and G. P. Salam, Phys. Lett. B **659** (2008) 119 [[arXiv:0707.1378](#)].
- [21] J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, Phys. Rev. Lett. **100** (2008) 242001 [[arXiv:0802.2470](#)].
- [22] D. Krohn, J. Thaler and L. T. Wang, JHEP **1002** (2010) 084 [[arXiv:0912.1342](#)].
- [23] S. D. Ellis, C. K. Vermilion and J. R. Walsh, Phys. Rev. D **81** (2010) 094023 [[arXiv:0912.0033](#)].